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Clumpy winds and the obscuration of Active Galactic Nuclei.

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ABSTRACT

The role of star-formation driven outflows in the obscuration of the central source in the Active Galactic Nuclei (AGN) is discussed. The outflow from a sub-parsec scale accretion disc is numerically modelled for parameters appropriate to the Galactic Centre. The resulting obscuration pattern is very patchy, with some lines of sight becoming optically thick to Thomson scattering. A fixed observer would see column depth changing by factors of many over time scales of order months to hundreds of years, depending on the physical size of the outflow region. Such winds may be relevant for obscuration of some AGN and especially "changing look AGN". However, averaged over the sky as seen from the central source, these winds are always optically thin unless wind outflow rates are super-Eddington. A simple scaling argument shows that this is true not only for stellar-driven winds but for any AGN winds. We therefore conclude that AGN winds are unable to account for the vast majority of optically thick obscured AGN (a significant fraction of all AGN). We suggest that the most likely source of optically thick obscuration in AGN is a warped parsec scale accretion disc.

Key words: Galaxy: centre – accretion: accretion discs – galaxies: active – methods: numerical

1 INTRODUCTION

According to the simplest version of the Unified model of Active Galactic Nuclei (AGN), the central source has fundamentally the same properties in all classes of AGN (e.g., Antonucci & Miller, 1985; Antonucci, 1993; Maiolino & Rieke, 1995; Risaliti et al., 1999; Sazonov & Revnivtsev, 2004). It is the orientation of our line of sight with respect to the dusty obscuring environment of an AGN that makes it appear as a type I (relatively un-obscured) or type II object (obscured). Despite of all the convincing observational evidence for the existence of the absorber, most frequently thought to be arranged in a shape of a torus, no convincing theoretical model has ever been produced to explain its properties. Recently, Nenkova et al. (2002) and Risaliti et al. (2002) demonstrated that to comply with the small observed torus sizes, the absorber must not be uniform in density but should be rather clumpy, i.e. consisting of individual smaller clouds. Theoretical models of clumpy tori (e.g., Krolik & Begelman, 1986, 1988; Vollmer et al., 2004), however, have all the same fundamental difficulty. As the observations require the torus to be geometrically thick, the velocity dispersion of the cold dusty clouds must be of the order of their orbital velocity in the inner parsec of a galactic centre. Optically thick tori would then have clouds colliding at super-sonic speeds many times during one dynamical time (Krolik & Begelman, 1986, 1988). Therefore, these models have to postulate (somewhat arbitrarily, in our point of view), that the clouds can survive these collisions, behaving in essence as rubber balls.

Recently, a number of authors argued that the obscuration must instead come from clumpy winds (e.g., Königl & Kartje, 1994; Kartje et al., 1999; Elvis, 2000; Elvis et al., 2004; Elitzur, 2005) emanating from the surface of an accretion disk, be these winds driven by line pressure (Proga, 2003), continuum radiation pressure, heating, or by hydromagnetic forces. In this paper we wish to critically assess this suggestion. In particular, we consider AGN winds driven by star formation activity in an accretion disc. Star or planet formation in AGN discs has been long predicted by theorists (Paczyński, 1978; Kolykhalov & Sunyaev, 1980; Lin & Pringle, 1987; Collin & Zahn, 1999; Gammie, 2001; Goodman, 2003), and recent observations of the young massive stars in the centre of our Galaxy (e.g., Genzel et al., 2003;

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Ghez et al., 2003) lend a very strong support to these theories (Levin & Beloborodov, 2003; Nayakshin & Sunyaev, 2005; Paumard et al., 2006). Using the SPH treatment of stellar winds developed by Cuadra et al. (2005, 2006), we calculate the obscuring properties of such winds for a specific example. We find that these winds have very irregular, patchy obscuration patterns. A fixed observer should then see the column depth through the wind varying on time scales from months or years to tens and hundreds of years, depending on the physical size of the wind launching region and the SMBH mass.

However, observations (see §3 below) suggest that the structure responsible for AGN obscuration should be optically thick over a large (e.g., a third) fraction of the whole sky. Our models cannot achieve such a high average line of sight column depth unless the mass loss rate in the wind is super-Eddington. In fact, we show via simple analytical estimates that this conclusion is valid whatever the nature of the wind driving mechanism is. We feel it would be very hard to produce highly super-Eddington winds in a plausible quasi steady-state AGN model for a typical (very sub-Eddington luminosity) AGN. Thus we suggest that winds, while very important for the AGN phenomenon, cannot replace the "torus" in its role in the unification schemes of AGN. Either the torus does exist despite the difficulties faced by the models, or another optically thick structure, e.g., a warped accretion disc plays its role in AGN.

2 STELLAR WINDS FROM AGN DISCS

AGN discs are expected to be massive and thus self-gravitating at large enough distances ($R \gtrsim 0.01 - 0.1$ pc) from the super-massive black holes (SMBH). If the disc cooling time is short, gravitational collapse and formation of stars or even planets is predicted (e.g., Paczyński, 1978; Kolykhalov & Sunyaev, 1980; Shlosman & Begelman, 1989; Gammie, 2001). Young massive stars in the central parsec of our own Galaxy were most likely created in this way (Paumard et al., 2006), with an apparent significant over-abundance of high mass stars (Nayakshin & Sunyaev, 2005) over their fraction in "normal galactic" star formation. As stars are born from the accretion disc, they launch powerful radiation fields and stellar winds, some of which will break through the disc. Low mass proto-stars may prove equally effective in launching winds in these circumstances as the rates at which gas is captured from the disk into the Hill (or capture) zones of the protostars are super-Eddington (Nayakshin, 2006). In addition, when the gas in the disk is depleted to about half its initial surface density, stellar velocity dispersion starts to grow, and soon the stellar disc becomes geometrically thicker than the gas disc (Nayakshin, 2006). Stellar winds then escape from above the disc directly.

We attempt to simulate this complex situation in a simplified setting, concentrating only on the wind part of it. For this reason we do not include the gas in the negligibly thin and flat accretion disc from which the stars are born. To capture a degree of the expected diversity of the stellar populations and conditions in this problem, the stars are divided into two groups. The first produces winds with velocities $v_{\rm w} = 300$ km/sec, whereas the second has $v_{\rm w} = 700$ km/sec. Both types of stars have mass loss rates of 2.5×10^{-4} M$_\odot$ year^{-1}, and are situated in a flat circularly rotating Keplerian disk of geometrical thickness $H(R) = 0.1R$ (the unit of length used here is 1 arcsecond at the distance of 8 kpc, which is about $1.2{\times}10^{17}$ cm or 0.04 pc). In total, we have 200 mass shredding stars, thus amounting to the mass loss rate of 0.1 M$_\odot$ year^{-1}, which is a factor of few super-Eddington for a SMBH mass of $\mathrm{M_{BH}} = 3.5 \times 10^6\,\mathrm{M}_\odot$. The disc inner and outer radii are $R_{\rm in} = 1.5$ and $R_{\rm out} = 8$, respectively. The stellar surface density follows the law $\Sigma_*(R) \propto R^{-1}$, and the stars are in the Keplerian circular rotation around the SMBH. The initial phase (i.e. the ϕ-coordinate) of the stars in the disk is generated randomly, as is the vertical coordinate within the $-H$ to $+H$ limits. Initially, the computational domain is filled with hot tenuous gas with velocity greater than the escape velocity. This gas quickly outflows from the region. At the end of the simulation stellar winds exceed the initial gas mass by a factor of few tens.

To perform simulations, we use the Gadget-2 code (Springel, 2005) modified to model stellar winds as new SPH particles ejected from the stellar wind sources. These methods were described and thoroughly tested in Cuadra et al. (2005, 2006).

A snapshot of the simulation is shown in Figure 1 at time $t \approx 2200$ years after the beginning of the simulation, which corresponds to ~ 36 dynamical times at $R = 1$. While there is no true steady state in this finite number of moving stars system, the snapshot is fairly typical of the morphology of the stellar wind. The face-on view (left panel) shows that some of the shocked wind managed to cool down and formed a small-scale disc. The inner part of the simulation domain is the most likely place for the disc to form since stellar wind density is highest there, leading to shocks, thermalization and rapid cooling; the frequent collisions of gaseous clumps "waste" momentum of the winds, and finally, the escape velocity from the region is around 600 km/sec, i.e. higher than wind velocities of the slower winds. With time the disc grows radially to both smaller and larger radii. However, the formation of the disc (cf. Cuadra et al., 2006) is physically significant only in the case when the gaseous accretion disc from which the stars were born is *entirely* absent, as is the case presently in the Galactic Centre. In the opposite case the cooled disc and the "spiral arms" seen at intermediate radii would simply blend in with the much more massive underlying gas accretion disc.

Contrary to the frequent collisions and high escape velocity in the inner region of the computational domain, the conditions in the outer regions allow direct escape of both the faster diffuse and the slower cooler clumpy winds. Due to the final extent of the stellar disc and the projection effect, the wind morphology reminds and "X"-shape (Figure 1, right panel). The edge-on view (right panel) of the stellar disc shows that the plane of the gas disc at $R \lesssim 2$ is very slightly tilted with respect to the orbital plane of the stellar disc. This is an artefact of the initial conditions.

The left panel of Figure 2 shows the obscuring column depth of the winds as seen from the SMBH. Since the orientation of the tilted inner disc is influenced by the initial conditions, we eliminate its obscuration, only plotting gas with radial distances $R \gtrsim 1.6$ from the SMBH, which excludes all of the disc. Besides, had we included in the simulations the more massive gas accretion disk whose midplane would coincide with that of the stars, the inner disc seen in Figure

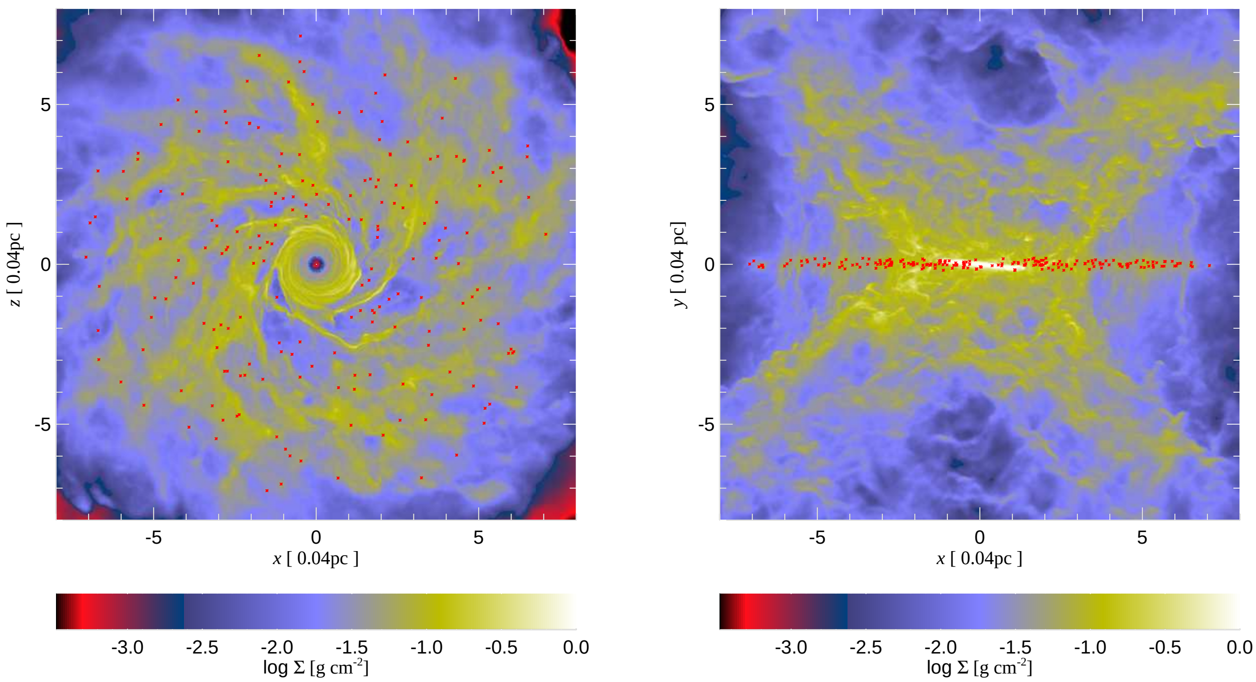

Figure 1. Face-on (left) and side (right) views of the simulation domain for the flat stellar disc configuration. Red asterisks show the location of the wind-producing stars used in the simulation (the red "dot" in the centre of the left panel is not a star, but a low column depth region centred on the SMBH).

1 would have completely blended in with the accretion disc and would not present much obscuration at all.

Note the very irregular patchy structure of the (yellow) optically thicker regions. The contrast between those and neighbouring less dense patches of sky is frequently a factor of 10 or more. Since the winds are rotating at a fraction of the local angular frequency, Ω, this implies that the column depth sampled by the observer will vary on time scales as short as $\sim 10^{-3}$ to 10^{-2} of $1/\Omega$, i.e. $t_{\rm var} \sim 0.04 - 0.4\,\rm year\ (R/0.1pc)^{3/2} M_8^{-1/2}$. The dotted pattern at the $\cos\theta = 0$ plane are the dense regions of stellar winds immediately next to the stars.

The right panel of Figure 2 shows the isotropic mass loss rate along the line of sight, defined as

$$\dot{M} \equiv \frac{\int d\Sigma\ 4\pi R^2 \rho v_R}{\int d\Sigma}\ , \qquad (1)$$

where the integral is taken along the line of sight defined by a given θ and ϕ. This quantity is useful for comparison with observations of AGN outflows. An observer has only one line of sight available at any given moment, and the assumption frequently made is that the outflow is roughly isotropic, thus $\dot{M} \sim 4\pi R^2 \rho v_R$. We find that there are lines of sight that yield isotropic mass outflow rates of $\sim 1 - 10\,\rm M_\odot$ year^{-1}, which is as much as a hundred times larger than the correct sky-averaged value. Also note that not all of the optically thicker regions seen in the left panel of figure 2 appear equally prominently in the outflow map in the right panel of the figure, as some of these structures have a small radial velocity or are even infalling to smaller radii.

3 COMPARISON TO OBSERVATIONS

Recent multi-wavelength observations (e.g., Jaffe et al., 2004; Packham et al., 2005; Prieto et al., 2005) indicate that AGN absorbers are relatively small, parsec-scale structures, rather than the extended (100 to 1000 parsec) ones as was thought a decade earlier on the basis of observations with poorer angular resolution. Nenkova et al. (2002) and Elitzur (2005) demonstrate that this observational fact demands the "torus" to be clumpy in order to allow high and low temperature regions to be simultaneously present at the same location in the torus. Nenkova et al. (2002) (see also Elitzur, 2005) show that the average number of clouds on the line of sight to the nucleus, $N_{\rm a}$, should be of the order of a few to ten. Let $M_{\rm c}$ be the mass of such a cloud, $M_{\rm c} = \Sigma_{\rm c}\pi R_{\rm c}^2$, and $\Sigma_{\rm c}$ and $R_{\rm c}$ be the surface density and cloud radius, respectively. In the model of these authors, the average column depth on the line of sight, $N_{\rm a}\Sigma_{\rm c}$ is of the order of 1 g cm^{-2} *or larger*, which is also reasonable given a large fraction of AGN that are Thomson-thick (e.g., Sazonov & Revnivtsev, 2004; Guainazzi et al., 2005). The total number of the clouds, $N_{\rm t}$, is connected to $N_{\rm a}$ through

$$N_{\rm a} = \frac{N_{\rm t}\pi R_{\rm c}^2}{2\pi R_{\rm t}^2}\ , \qquad (2)$$

where $R_{\rm t}$ is the typical radius of the torus, and we assumed that it covers roughly 2π of the sky as seen from the SMBH. Now, assume that the torus is made up of clouds that form in the outflowing disk wind, as in the simulations presented in this paper. The total mass outflow rate of the clouds is then

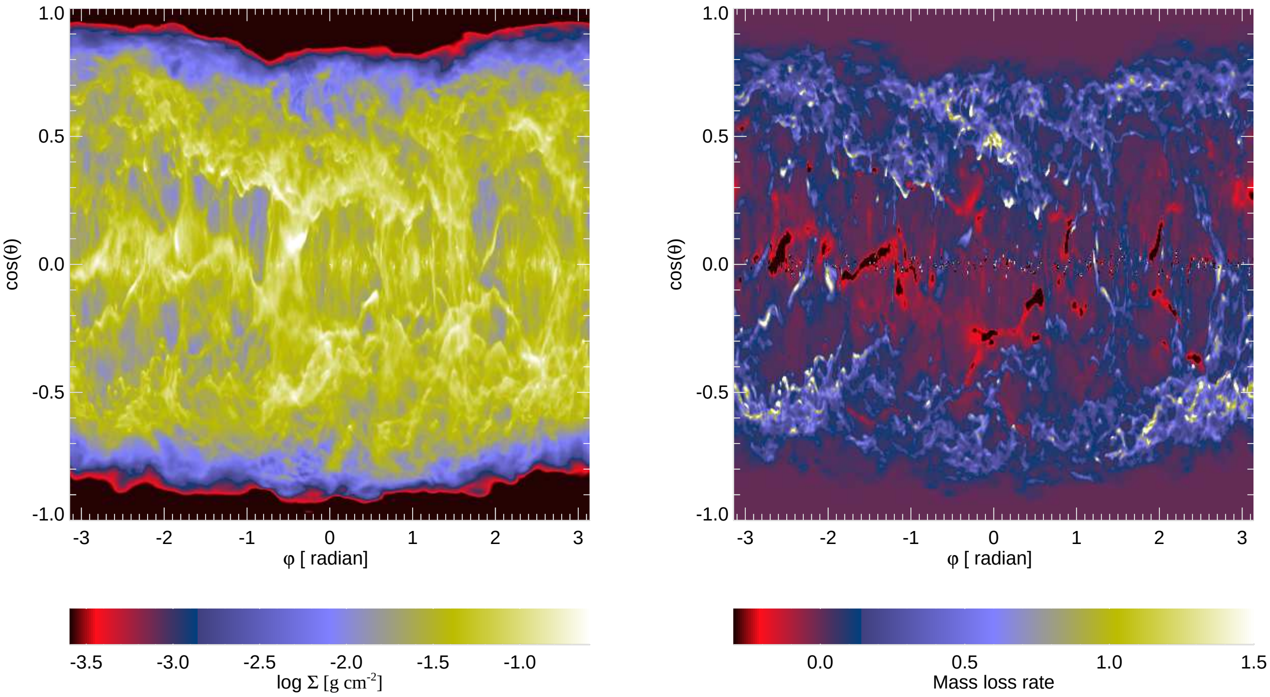

Figure 2. Column depth through the wind (left) and isotropic mass outflow rate (right; in units of $\mathrm{M}_\odot$ year^{-1}) for the simulation shown in Fig. 1. Note the large variations of the obscuring column depth over small angular scales. The gaseous inner disc seen in the left panel of Figure 1 has been excluded from these Figures.

$$\dot{M}_{\rm wind} \sim 2\pi R_{\rm t}^2 N_{\rm a} \Sigma_{\rm c} \Omega_{\rm K} \sim 15 \frac{\mathrm{M}_\odot}{\rm year}\; N_{\rm a}\Sigma_{\rm c} \left(\frac{R_{\rm t}}{1\ \rm pc}\right)^{1/2} M_8^{1/2}\ , \quad (3)$$

where M_8 is the SMBH mass in units of $10^8\,\mathrm{M}_\odot$, and we assumed that clouds radial velocities are of the order of the local Keplerian speed. Now, the Eddington accretion rate is $4\pi G\,\mathrm{M}_{\rm BH} m_{\rm p}/\epsilon c \sigma_{\rm T} \approx 2\,\mathrm{M}_\odot \mathrm{year}^{-1} M_8$. Thus the required wind mass loss rate (equation 3) is an order of magnitude higher, typically, than the Eddington accretion rate for a $M_8 \sim 1$ object and a parsec-scale torus. The estimate of $\dot{M}_{\rm wind}$ could be reduced somewhat by postulating even smaller torus sizes, but it is hard to make $R_{\rm t}$ much smaller than ~ 0.1 pc as then the dust would be sublimated by the AGN radiation field (e.g., eq. 3.2 in Emmering et al., 1992). However, we rather think that estimate 3 is too optimistic, e.g. that an even higher mass outflow rates are needed, as the observations and modelling of optically thick sources require a *minimum* absorbing column depth, and hence in a good fraction of sources $N_{\rm a}\Sigma_{\rm c}$ may actually be much higher than 1 g cm^{-2}.

Considering a specific case of the local obscured AGN studied by (Guainazzi et al., 2005), we note that the bolometric luminosities of these objects in the infrared, X-ray and optical bands are in the range $L \sim 10^{43} - \text{few} \times 10^{44}$ erg/sec, which implies SMBH accretion rates of "only" $\sim 0.01\,\mathrm{M}_\odot$ year^{-1} for the standard radiative efficiency. Hence if the obscuration of the optically thick objects in that sample were provided by the winds, we would conclude that the SMBH accretion process must be very wasteful, with $\sim 100 - 10{,}000$ times more mass flowing out of the inner parsec than accreting on the SMBH. (Note that these moderately bright AGN are not likely to be in the non-radiative accretion flow regime when vigorous outflows are in fact expected, e.g., Blandford & Begelman, 1999) It would also require a very high mass influx into the inner parsec to sustain such winds. Given the difficulty of delivering enough fuel to the SMBHs even in the earlier gas-rich epochs (Thompson et al., 2005), it is hard to see how such high mass influxes could be maintained.

4 DISCUSSION AND CONCLUSIONS

Accreting black holes can drive strong outflows via X-ray heating, line or continuous radiation pressure, and hydromagnetic forces (e.g., Begelman et al., 1983; Königl & Kartje, 1994; Kartje et al., 1999; Proga, 2003). Star formation on the outskirts of cool massive accretion discs will also result in winds driven by outflows from the young massive stars (Cuadra et al., 2005). Here we studied the obscuration properties of the AGN outflows of the last type. We found that these outflows are quite clumpy, with the lines of sight passing through the clumps becoming moderately optically thick to Thomson scattering for high enough wind mass loss rates. Such outflows are bound to play a role in the obscuration of AGN.

We however feel that this role cannot be dominant as the sky averaged column depth is significantly smaller than the one required by the current "torus" models (e.g., Nenkova et al., 2002; Elitzur, 2005) and observations (Guainazzi et al., 2005) for realistic mass outflow rates, e.g. comparable to the accretion rates onto the SMBH, which are likely to be only $0.01 - 0.1$ of the Eddington accretion rates in the local AGN (and are much smaller if we also

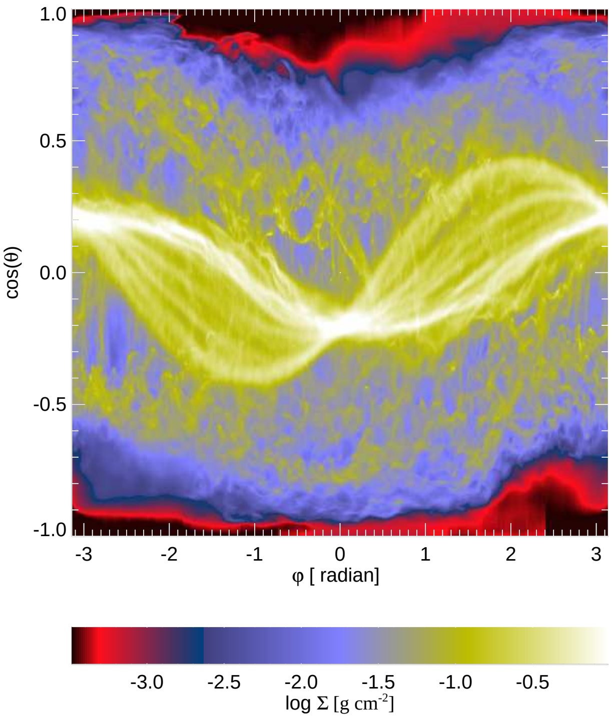

Figure 3. Same as the left panel of Figure 2 but for slightly different initial conditions and with the cold tilted and warped inner disc included in the Figure. Notice that this very light (only $\sim 3\,M_\odot$) disc is a very efficient absorber.

consider Low Luminosity AGN; see, for example, Fig. 1.9 in Ho, 2005). We thus believe that the search for the culprit of the optically thick obscuration of AGN should still go on.

One rather obvious candidate is a warped accretion disc. The disc may be significantly warped by instabilities due to back reaction to mass outflow or due to the AGN radiation pressure, or it may be warped due to precession in a non-axisymmetric gravitational potential (e.g. Schandl & Meyer, 1994; Pringle, 1996; Nayakshin, 2005). Finally, there is no reason for an initial disc configuration to be flat if the mass deposition is much shorter than the disc viscous time, which was probably the case in the Galactic Centre (Nayakshin & Cuadra, 2005; Paumard et al., 2006). A simulation ran by us for the present paper and later rejected (because the initial mass of the gas turned out too high so that it influenced the outcome of the simulation) is curiously useful in this respect. Figure 3 shows the obscuration pattern of this simulation in the same way as in the left panel in Figure 2, but including the tilted and slightly warped gas disc. Except for the initial conditions, this simulation is exactly identical to the one shown in Figures 1 & 2. As Figure 3 shows, the obscuration provided by the winds literally pales in comparison with that produced by the warped disc, whose mass is only $\sim 3\,M_\odot$. An accretion disc is a long lived structure that can accumulate a lot of gas (still a small fraction of the SMBH mass, however) and can be Thomson-thick out to parsec distances. Obscuration by a warped accretion disc requires *no* continuous energy input, and would work for low or high luminosity AGN as long as the discs are sufficiently massive and strongly warped.

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